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Chapter 3

A Brief Survey of Possible Mechanisms in Information Processing

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I shall try to give an outsider's view of what invertebrate studies may contribute to learning research. Although I have not conducted studies on invertebrates, I have been interested in them for a long time. When I was with the Atomic Energy Commission, one of the first proposals which came across my desk was from Jim McConnell on planarian research. Considering the trouble that I had getting that proposal approved, I have had an interest in this field ever since, mainly to see whether half of what he proposed back in 1958 has been feasible or not.

My own particular interest is human engineering, as we have investigated the general questions: How much information can a human transmit, and how does he go about it? This is quite far removed from your general area of consideration, and yet I should like to use, as a framework, some of our findings to indicate places where I think invertebrate research could be quite useful. In particular, I shall briefly describe the elements shown in Fig. 1 which we conclude are part of the human operator.

When we started this research in 1952 at the University of Illinois, our first inquiries were: What is the optimum amount which a human can process? Specifically we had experts perform well-learned tasks, such as typing, piano playing, mental arithmetic, etc. By using random texts so they could not rely simply on memory, we found that most people have a capacity of fifteen to twenty-five bits per second (Quastler and Wulff, 1955; Quastler, 1956; and Augenstein and Quastler, 1967); only when outstanding readers are recognizing random words are performances observed as high as about forty bits per second (Pierce and Karlin, 1957).

We next asked: What determines this overall capacity? At least three operations must be performed to transduce information: inputting, processing, and outputting.

We could immediately rule out the outputting as being rate-limiting simply because, if you allowed the pianists to memorize their random text, they could improve their performance by a factor of 2 or 3.

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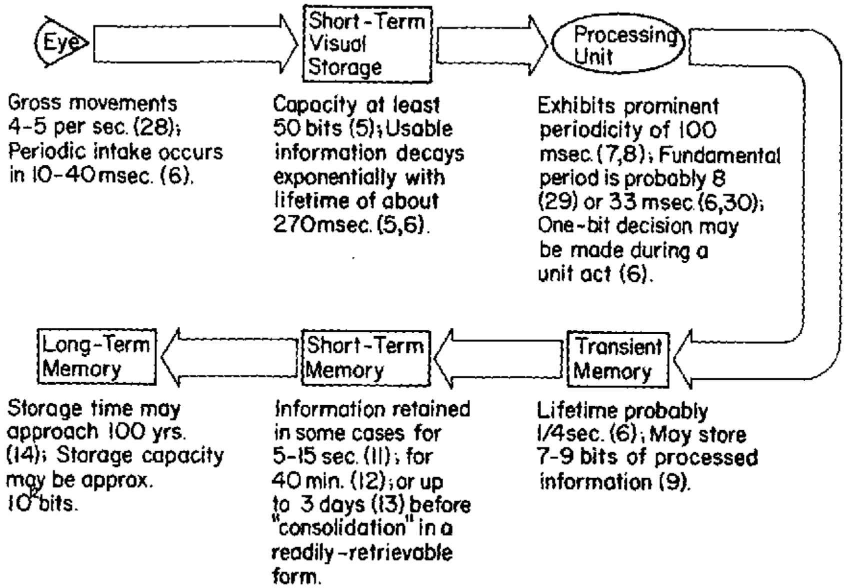

Fig. 1. Schematic representation of elements involved in information processing by humans.

To pursue further these questions, we (and other laboratories) ran a number of experiments to isolate, insofar as possible, the input mechanism and define its capabilities. Let me describe just one experiment carried out at Bell Laboratories which tells us a lot about the input mechanism in humans (Auerbach and Coriell, 1961). They displayed on a television screen a card with 16 randomized letters in two rows of 8 letters each. This was flashed for 40 msec, and then another card with a black marker either below or just above one of the positions was placed in front of a second camera and flashed for 40 msec onto the same monitor. As soon as this latter marker appeared, the subjects were to identify the letter designated.

When the marker actually was shown 40 msec before the letters, the subjects identified the correct letter 70% of the time. When letters and marker came simultaneously, they got 65% correct, this corresponded to an intake of over 50 bits. When the marker was flashed after the letters appeared, the percentage correct decreased as the interval increased; in fact, when the percentage correct was plotted versus the interval between display and marker, the data could be fitted with an exponential having a decay constant of 270 msec.

We did similar experiments with playing cards, but in these the subject found out which item of the display he was to identify only after the display had been terminated for 2 sec. Interestingly enough when we exposed our cards for 40 msec, the value of 15 bits which our subjects could transmit agreed very closely with the value obtained by the Bell

Laboratory group when they used an interval of 2 sec between letters and marker. We also found that the amount of information which can be transmitted about a display illuminated for 100 msec is the same as that for 40 msec. Only for display durations of more than 250 msec is there an increase in performance, and for 10-msec illumination the transmission is only eight bits (Augenstein, 1956).

From these results, we conclude that in 10 to 40 msec the eye can take in and temporarily store away in a usable form at least 50 bits of information, but that this short-term storage decays away with a lifetime of about $\frac{1}{4}$ sec. Further, these results plus earlier information on eye movements during reading imply that the eye can take in such large amounts of information four or five times per second, presumably in conjunction with gross eye movements. These results clearly indicate that the input mechanism is not the rate-limiting process, and thus the limitations must occur in the processing unit.

Let me describe one of a number of experiments we used to investigate the properties of data processing in humans. A card containing a column of randomized letters and numbers was put up in front of the subjects in the dark. Their task was to push a switch (i.e., the task was self-paced) to illuminate the display and then to scan down until they found the first number, release the switch, and tell us the number. When we made a histogram of how often a given response time occurred, the distribution was not at all random. Rather, we found very strong evidence of a 100-msec periodicity, which we initially assumed to be associated with the alpha rhythm (Augenstein, 1955). However, it is now fairly clear that this is the predominant but not the fundamental periodicity; presumably it is a collection of three 33-msec or twelve 8-msec or seventeen 6-msec periods, etc. (Augenstein, 1958). Of great interest is the fact that we found the same kind of periodic behavior, independent of the complexity of the task, i.e., for simple scanning experiments, adding columns of numbers, or typing.

This immediately suggested, although it certainly is not proven, that during the performance of simple tasks, at least, the human processing involves some common type of decision, presumably either on a binary or trinary basis. In fact, the basic hypothesis we continue to test is that during one of these unit acts a human either takes in a large batch of data or makes a one-bit decision.

There is fragmentary evidence that, once decisions are made by the computer unit, the processed information goes into a storage unit, again having a characteristic duration of about $\frac{1}{4}$ sec. Such a unit would be consistent with Miller's seven- to nine-bit chunk hypothesis (Miller, 1956). Also the data for delayed auditory feedback may depend upon such a storage, providing that a feed-back checking mechanism connects this unit and the ear [note that optimum interference occurs when the delay between speaking and hearing is 210 to 300 msec (Fairbanks, 1955)].

Following this temporary storage the information apparently resides in a so-called short-term memory for times varying presumably from 5 sec

(Chorover and Schiller, 1965 and 1966) to 40 min (Jarvik, 1964, and McGaugh, 1966)—or perhaps even 3 days in some cases (Flexner *et al.*, 1965)—before "incorporation" into the "permanent" memory. Recall elicited from implanted electrodes suggests that the duration of storage in the permanent memory may even be as much as 100 years (Penfield, 1959).

This cursory description is not meant to be necessarily all inclusive or even to convince you of the validity of the representation in Fig. 1. Rather, it was designed to call attention to specific elements in the information-processing scheme about which invertebrate research might provide information.

Biochemical studies in planaria have already generated important questions about the chemical basis of memory (Corning, Chapter 18 in this book). In spite of the controversy about these experiments I am confident they will be continued. Also, I have always watched the planaria cannibalism experiments (McConnell, Chapters 14 and 20 in this book) with great interest and hope that this phenomenon can be shown to operate conclusively. If so, it could provide a system for studying how one cell, or at least a small group of cells, may adapt or modify neighboring cells so as to create a processing unit which would ultimately modify behavior. This whole question must be attacked in a very rigorous way in a number of different organisms since clearly neurons can be adapted, i.e., their behavior can be drastically changed. Upon what does this depend? Are there cell-wall changes similar to those induced in paramecia by different agents (Sonneborn, 1963) or similar to those induced by virus or sperm transformation (Smith, 1963, and Rothschild, 1956)? If so, is this what is important in the storage of long-term memory?

In planaria the gut is so primitive that apparently whole cells are ingested (Quastler, 1962). Further, 20 to 25% of planarian cells are essentially undifferentiated (McConnell, 1965). Thus, if learning is transferred by cannibalism, it should be of great interest to investigate whether, when a "learned cell" is introduced into a host, it can act as an organizer to determine the differentiation of these "uncommitted" cells and thus "consolidate" the transferred information. That certain cells can be crucial in adapting others is well known in a number of embryological systems. Once a cell is adapted and information is stored, it still must be retrieved to be of any value. How does this occur? By a change in membrane resistance (Augenstein, 1962, and Augenstein and Van Zytveld, 1964)? By an antigen-antibody type of reaction (Silverstein, 1963)? Whether invertebrate preparations can be used to pursue this question remains to be seen.

Our results on periodicity in human processing call attention to another important problem: What mechanisms account for immediate processing? Since the unit processing time is of the order of a few milliseconds, data processing cannot involve the synthesis of a macromolecule (Augenstein, 1962; Augenstein and Quastler, 1967; and Augenstein and Van Zytveld, 1964); i.e., to synthesize a protein or nucleic acid requires at least 10 to 30 msec *per monomer unit* incorporated. Thus, the unit operating time for immediate processing must reflect a time constant for a network of cells (McCulloch and Pitts, 1943) or a coupled enzyme system or perhaps conformation changes in proteins which control the flow of current at a synapse (Augenstein, 1962, and Augenstein and Van Zytveld, 1964). Perhaps the Limulus preparation used by Corning, Feinstein, and Haight (1965) may provide some insight into this problem.

Of course the biggest question in all behavioral research is: What is the code by which information is represented internally? Is it binary, trinary, or something more esoteric? Unfortunately, I don't know how to do critical experiments in this area, and, again, this must be attacked at many levels. Thus, if one of you could find some means of determining the code by which information is stored in a single cell, this would be a tremendous step forward. More specifically, is only one bit stored in a single adapted cell or at a single synapse, or is much more than that stored? Once we can say meaningful things about this question, I am sure it will become much easier to determine the chemical basis of memory storage.

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